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We present theoretical results on the $^{208}Pb(\nu_e, e^-)^{208}Bi$ and $^{208}Pb(\nu_\mu, \mu^-)^{208}Bi$ reaction cross sections as a function of neutrino energy obtained within the charge-exchange Random Phase Approximation. A detailed knowledge of these cross sections is necessary to assess the possibility of using lead as a detector in future experiments on supernova neutrinos, such as OMNIS and LAND, and possibly detecting neutrino oscillation signals by exploiting the spectroscopic properties of ^{208}Bi excited in the charged-current neutrino-^{208}Pb reaction. Effects resulting from the way Coulomb corrections are treated are also discussed.

The study of reactions induced by neutrinos on nuclei is at present an active field of research. A detailed knowledge of the reaction cross sections is interesting for different domains, going from high energy physics to astrophysics [1]. For example, they are necessary in the interpretation of current experiments on neutrinos as well as in the evaluation of possible new detectors for future experiments. The importance of neutrino-nuclei reactions in astrophysical processes, such as the r-process nucleosynthesis, is also being attentively studied [2,3]. In particular, $\nu - Pb$ reactions have attracted much interest recently. Lead has been used as a shielding material in the recent experiments on neutrino oscillations performed by the LSND collaboration [4,5] so that estimates of the $\nu - Pb$ reaction cross sections are necessary for the evaluation of backgrounds in these experiments; also projects on lead-based detectors [6], such as OMNIS [7,8] and LAND [9], are being studied for the purpose of detecting supernova neutrinos. These detectors might provide information on neutrino properties, such as oscillations in matter [10] or the mass by measuring the time delay and/or spreading in the neutrino signal [8,9] as well as help in testing supernova models. From the practical point of view, lead-based detectors seem to present several of the characteristics required to be supernova observatories, namely high sensitivity to neutrinos of all flavors, simplicity, reliability with inexpensive materials [9]. Large cross sections for neutrinos in the supernova energy range are also an important condition since they determine the possible rates and therefore the maximum observable distance. Actually, ν-nucleus reaction cross sections increase strongly with the charge of the nucleus. For example, if the neutrinos come from the decay-at-rest (DAR) of μ^+, the cross sections of the flux-averaged charged-current (CC) reaction $\nu_e +_Z X_N \rightarrow_{Z+1} X'_{N-1} + e^-$ goes from about 5.4 10^{-42} cm^2 for ^{12}C [11–13], to 2.38 10^{-40} cm^2 in ^{56}Fe [14] and is calculated to be 5.96 10^{-39} in ^{208}Pb [15]. Besides these practical features which are essential in the choice of the nucleus to use to detect neutrinos, another important feature is the spectroscopic properties which may suggest attractive signals of supernova neutrino oscillations. In [10], for example, it has been shown that the measurement of events where two neutrons are emitted by ^{208}Bi excited in the reaction $\nu_e +^{208} Pb \rightarrow^{208} Bi + e^-$ is both flavor-specific and very sensitive to the mean energy of the ν_e. In case when $\nu_\mu, \nu_\tau \rightarrow \nu_e$ oscillations take place, the hotter ν_e would increase the number of two neutron events by a factor of forty [10]. Another possible signal has been proposed in [15], that is that the energy distribution of the neutrons emitted in the same CC reaction should have a peak at low energy more or less pronounced according to whether the oscillations occur or not. This peak would come from the excitation of a peak at around 8 MeV in the Gamow-Teller strength distribution. (One should however note that this peak has never been observed experimentally). Both the estimate of the CC $\nu - Pb$ reaction cross section in [10] and the microscopic calculations of [15] show that a possible oscillation signal relies strongly on the knowledge of the spectral properties of ^{208}Bi. In fact, the CC reaction cross section induced by ν_e scales almost as the square of the electron energy and is particularly sensitive to the detailed structure of the excitation spectrum as was already pointed out for the case of ^{12}C [16]. It is then important either to get the cross sections directly from the experiment or/and to obtain different theoretical estimates in order to know the theoretical uncertainties and how they affect the reaction cross sections. This is crucial when the impinging neutrino energy increases because not only the allowed Gamow-Teller (GT) and Isobaric Analogue State (IAS) contribute significantly to these cross sections but also forbidden transitions, of first-, second-, third-order (which are not very well known experimentally).

In this paper, we present new theoretical results for the CC $\nu_e +^{208} Pb \rightarrow^{208} Bi + e^-$ reaction cross section. Our calculations, as opposed to [15], are performed in a <u>self-consistent</u> charge-exchange Random-Phase-Approximation (RPA) with effective Skyrme forces. The neutrino energy spans a large range because of the various processes considered, such as future experiments with astronomical neutrinos, recent terrestrial experiments such as the LSND ones [15] or the r-process nucleosynthesis. We prefer to give non flux-averaged cross sections obtained for both low-energy ν_e and high-energy ν_e, ν_μ, over the range determined by the energies of the decay-in-flight (DIF) of μ^+ and π^+. Flux-averaged DAR and DIF cross sections are given in the latter case and compared with the results in [15]. Concerning low-energy neutrinos, these cross sections may be used to convolute with different energy spectra from different supernovae models (their average energy and details are still subject to uncertainties). We also show the importance of the contribution of forbidden transitions and how it evolves as a function of neutrino energy. This is often not taken into account in many present r-process nucleosynthesis calculations and so the neutrino-nuclei cross sections are underestimated as pointed out in [17] for first forbidden transitions.

The general expression for the differential cross section as a function of the incident neutrino energy E_ν for the reaction $\nu_l +^{208} Pb \rightarrow l +^{208} Bi$ $(l = e,\ \mu)$ is [18,19]

$$\sigma(E_\nu) = \frac{G^2}{2\pi} cos^2\theta_C \sum_f p_l E_l \int_{-1}^{1} d(cos\,\theta) M_\beta, \tag{1}$$

where $G\,cos\,\theta_C$ is the weak coupling constant, θ is the angle between the directions of the incident neutrino and the outgoing lepton, $E_l = E_\nu - E_{fi}$ (p_l) is the outgoing lepton energy (momentum), E_{fi} being the energy transferred to the nucleus, M_β are the nuclear Gamow-Teller and Fermi type transition probabilities [19].

In a nucleus as heavy as Pb the distortion of the outgoing lepton wavefunction due to the Coulomb field of the daughter nucleus becomes large and affects the integrated cross section considerably. In our treatment of this effect we follow the findings of ref. [20]. In ref. [20] it is found that the "Effective Momentum Approximation" (EMA) works well for high energy neutrinos. This approximation consists in using an effective momentum $p_l^{eff} = \sqrt{E_{eff}^2 - m^2}$ where $E_{eff} = E - V_C(0)$ ($V_C(0)$ is the Coulomb potential at the origin) in calculating the angle integrated cross section and multiplying eq.(1) by $(p_l^{eff}/p_l)^2$. It is also shown that the Modified EMA (MEMA) works better than EMA for ν_μ of low and high energies. In this approximation eq.(1) is multiplied by $p_l^{eff} E_{eff}/p_l E_l$. We use therefore this method in all our calculations of the (ν_μ, μ^-) cross sections. In the case of the (ν_e, e^-) process, the situation is somewhat more complicated. The Fermi function works only for very low energies, namely $E_e \leq 10\ MeV$ (where $p_e R \ll 1$, R is the nuclear radius), whereas the MEMA seems to be a good approximation for most energies of the outgoing electrons [20]. We adopt this procedure in our calculations although the accuracy of our calculations might be smaller for neutrinos with very low energies.

To get flux-averaged cross sections it is necessary to convolute (1) by the neutrino flux $f(E_\nu)$, that is

$$\langle\sigma\rangle_f = \int_{E_0}^{\infty} dE_\nu \sigma(E_\nu) f(E_\nu), \tag{2}$$

E_0 being the threshold energy. The choice of $f(E_\nu)$ depends on the neutrino source and can be taken for example equal to the supernova neutrino energy spectrum given by transport codes or the neutrino fluxes produced by a beam dump.

The nuclear structure model used to evaluate the transition probabilities M_β in (1) is the charge-exchange Random-Phase-Approximation (RPA). The details of the approach can be found in [21]. The calculations we present have been obtained in a self-consistent approach: the HF single-particles energies and wavefunctions as well as the residual particle-hole interaction are derived from the same effective forces, namely the SIII [22] and SGII [23] Skyrme forces. We have found that the model configuration space used is large enough for the Ikeda and Fermi sum rule to be satisfied as well as the non energy-weigthed and energy-weighted sum rules for the forbidden transitions [24].

We have calculated the differential cross sections for the reactions $^{208}Pb(\nu_e, e^-)^{208}Bi$ (figs.1,2) and $^{208}Pb(\nu_\mu, \mu^-)^{208}Bi$ (fig.3) as a function of the neutrino energy for a mesh of energies, i.e. $\Delta E = 2.5\ MeV$ for $E_{\nu_e} \leq 52.5\ MeV$ and $\Delta E = 5.0\ MeV$ for $E_{\nu_l} \geq 52.5\ MeV$ $(l = e, \mu)$. The results shown have been obtained with the SIII force, but we have found that with the SGII force we get quite similar results. We have included all the multipolarities with $J \leq 6$ and checked that the contribution coming from $J = 7$ is small. (For higher multipolarities a mean field description, neglecting the particle-hole residual interaction, can be used to evaluate the transition probabilities (1)). In fig.1 we show two graphs for the (ν_e, e^-) inclusive cross section with $E_{\nu_e} < 52.5\ MeV$, one evaluated with the Fermi function (dotted line) and the other (solid line) computed using the MEMA approximation for the Coulomb distortions of the outgoing electron. We see that the two curves are quite different demonstrating that the treatment of the Coulomb distortions is an important ingredient in the calculation of the charged current neutrino reactions in heavy nuclei. The wiggles in the solid line reflect the dependence of the amplitude on the excitation energies of those states in $^{208}Bi^*$ that contribute significantly to the inclusive cross section. In figs.2 and 3 we show the (ν_e, e^-) $(E_{\nu_e} > 52.5\ MeV)$ and (ν_μ, μ^-) inclusive cross sections, both obtained with the MEMA approximation. The behaviour of these cross sections as a function of the neutrino energies is, as expected, very similar for ν_μ and ν_e, the only difference coming from the mass threshold.

Figures 4,5,6 show the contribution of the different multipolarities to the total cross section in the MEMA approximation (fig.1), for the impinging neutrino energies $E_{\nu_e} = 15, 30, 50\ MeV$, which are characteristic average energies for supernovae neutrinos. When

$E_{\nu_e} = 15\ MeV$ (fig.4), σ_{ν_e} is dominated by the allowed Gamow-Teller ($J^\pi = 1^+$) transition, but already one component of the spin-dipole ($J^\pi = 0^-, 1^-, 2^-$) gives a significant contribution. As the neutrino energy increases (fig.5), the allowed IAS and other forbidden transitions ($J^\pi = 2^+, 3^+$) start to contribute significantly. Finally, we see that, when $E_{\nu_e} = 50\ MeV$ (fig.6), the GT and IAS transitions are not dominating at all, the cross section is being spread over many multipolarities. These results suggest that r-process nucleosynthesis calculations such as [3], which include neutrino-nuclei reactions, should take into account forbidden transitions. This may be even more important if $\nu_\tau, \nu_\mu \rightarrow \nu_e$ oscillations occur, because in this case electron neutrino may have a higher average energy than it is usually expected from current supernovae models.

Using eq.(2) we have calculated the total inclusive flux-averaged cross sections by convoluting the energy dependent neutrino cross sections (figs.1,3) with the neutrino fluxes for both ν_μ coming from the DIF of π^+ and ν_e coming from the DAR of μ^+. The neutrino fluxes $f(E_\nu)$ were taken from [25]. These neutrino fluxes have been used in the recent experiments $\nu_\mu \rightarrow \nu_e$ [4,26], $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [5,27] or $\nu_\mu \rightarrow \nu_x$ [28] performed by the LSND and KARMEN collaborations. The $DAR(\nu_e, e^-)$ cross section calculated using the Fermi function is $\sigma_{DAR} = 70.4 \cdot 10^{-40}\ cm^2$; while the one calculated in the MEMA is $56.2 \cdot 10^{-40}\ cm^2$. The $DIF(\nu_\mu, \mu^-)$ is $\sigma_{DIF} = 399 \cdot 10^{-40}\ cm^2$. These results are comparable with the values $\sigma_{DAR} = 59.6 \cdot 10^{-40}\ cm^2$ (obtained with the Fermi function) and $\sigma_{DIF} = 319 \cdot 10^{-40}\ cm^2$ obtained in [15]. We see that there is a 20% difference with the results in [15] in the DAR cross section if the Coulomb distortions are treated in the same way (the Fermi function). This difference is due to the very strong sensitivity of this cross section to the energies of the excited states as was already pointed out in [16]. If we use the MEMA approximation, our cross section changes by $20 - 30\%$. As figure 1 shows, the two cross sections have a quite different behaviour as a function of the neutrino energy so that this difference on the flux-averaged cross section may vary according to the particular neutrino source considered.

As mentioned, two possible neutrino oscillation $\nu_\mu, \nu_\tau \rightarrow \nu_e$ signals based on the spectroscopic properties of ^{208}Bi excited in the CC reaction have been proposed recently. In [10], it was shown that the 2-neutron events associated with the deexcitation of ^{208}Bi are very sensitive to the mean electron neutrino energy. This signal relies on the fact that most of the IAS, GT and first-forbidden strength distributions are above the $2n$ emission threshold ($14.98\ MeV$) in ^{208}Bi. Our results show that not only the allowed and spin-dipole strengths are above this threshold, but also a fraction of the strength distributions associated with other forbidden transitions (fig.5) will contribute to the $2n$ decay. All the arguments given in [10] are based on the statistical calculations of $1n$ and $2n$ decays. The direct $1n$ emission represents about 50% of the total width in the case of the IAS, and $5 - 10\%$ in the case of the GT [21].

In [15], it was pointed out that the energy distribution of the neutrons in the $1n$ events should form a peak at low energy, more or less pronounced according to the occurence or absence of oscillations. This peak comes from the GT strength distribution at around $7.6\ MeV$ which is located above the $1n$ threshold emission at $6.9\ MeV$. Our GT distribution also shows a peak at around $7.5\ MeV$. We have checked that its location is not sensitive to the choice of the effective forces used. Still one should be careful about conclusions, because predictions of different models about the energy location and strength of that peak are at variance.

In summary, we have calculated the $^{208}Pb(\nu_e, e^-)^{208}Bi$ and $^{208}Pb(\nu_\mu, \mu^-)^{208}Bi$ reaction cross sections in a self-consistent charge-exchange Random-Phase-Approximation with Skyrme effective forces. The differential cross sections as a function of neutrino energy are given. They can be employed in the interpretation of the recent experiments on neutrino oscillations performed by the LSND collaboration (where reactions induced by neutrinos on lead contribute significantly to the background) as well as for the projects under study in which lead should be used to detect supernova neutrinos. We have also given the flux-averaged reaction cross sections with ν_μ coming from the DIF of π^+ or with ν_e coming from the DAR of μ^+, in comparison with other recent microscopic calculations. We have also studied the effect of Coulomb distortions and the way these are introduced in the calculation of cross sections. For the DAR ν_e cross sections we find changes of $20 - 30\%$ depending on whether the Fermi function or the modified Effective Momentum Approximation is used. Finally, we have shown that forbidden transitions contribute significantly to the neutrino-nuclei reaction cross sections even at the "astrophysical neutrino energies" and they should be included in present r-process nucleosynthesis calculations.

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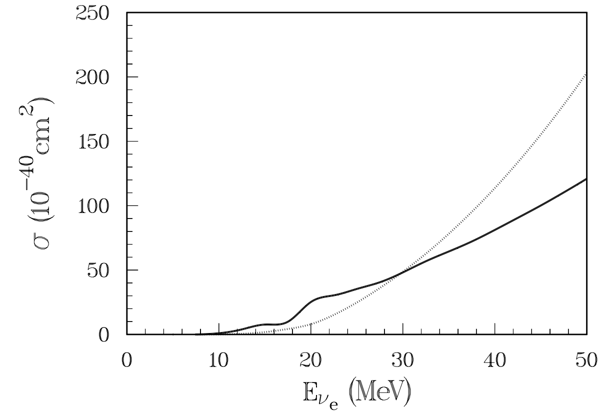

FIG. 1. Differential $^{208}Pb(\nu_e,e^-)^{208}Bi$ cross section as a function of electron neutrino energy ($E_{\nu_e} < 52.5\ MeV$) for a mesh of energies ($\Delta E = 2.5\ MeV$). The two curves show the results obtained with two different treatment of the Coulomb distortions : i) the Fermi function (dotted line) and ii) the Modified Effective Momentum Approximation (solid line).

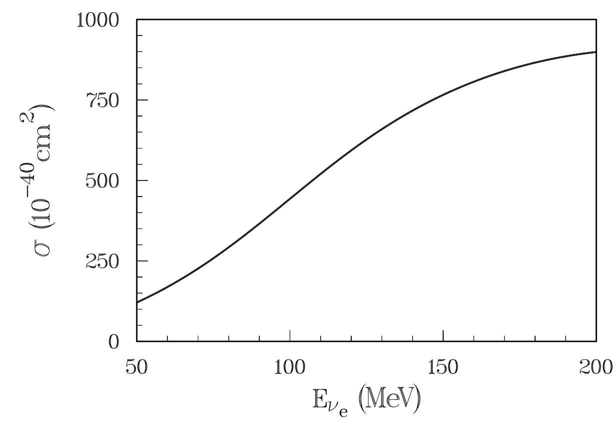

FIG. 2. Differential $^{208}Pb(\nu_e,e^-)^{208}Bi$ cross section as a function of electron neutrino energy ($E_{\nu_e} > 52.5\ MeV$) for a mesh of energies ($\Delta E = 5.0\ MeV$), obtained with the MEMA approximation.

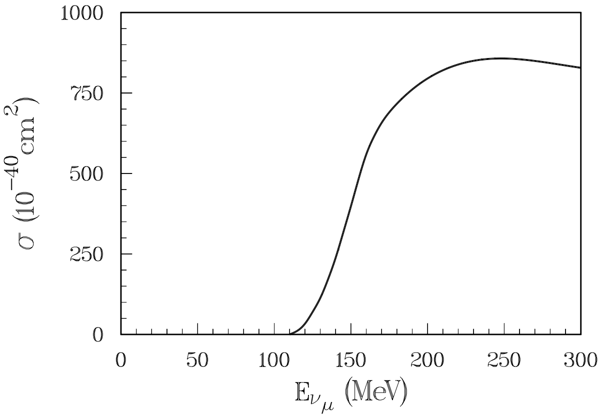

FIG. 3. Differential $^{208}Pb(\nu_\mu,\mu^-)^{208}Bi$ cross section as a function of muon neutrino energy for a mesh of energies ($\Delta E = 5.0\ MeV$), obtained with the MEMA approximation.

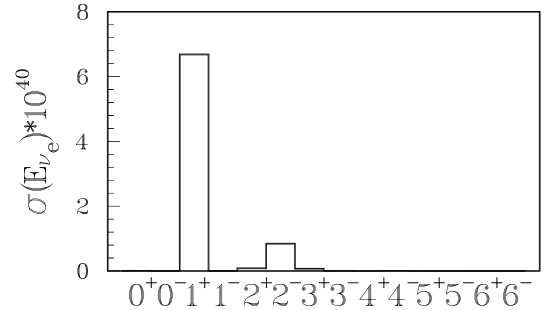

FIG. 4. Contribution of the different multipolarities to the differential $^{208}Pb(\nu_e,e^-)^{208}Bi$ cross sections ($10^{-40}\ cm^2$) for $E_{\nu_e} = 15\ MeV$, obtained with the MEMA approximation.

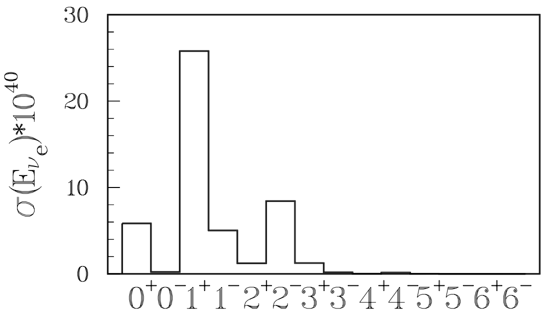

FIG. 5. Same as fig.4 but for $E_{\nu_e} = 30\ MeV$.

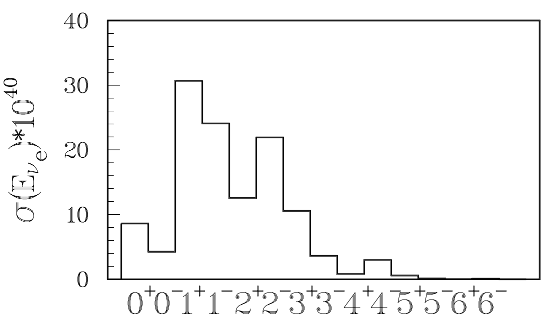

FIG. 6. Same as fig.4 but for $E_{\nu_e} = 50\ MeV$.